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6. AUTHOR(S)
Meng Zhou
Thomas M. Powell
Mark E. Huntley

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
Scripps Inst. of Oceanogr.
UC San Diego
La Jolla, CA 92093-0202

Dept. of Integrative Bio.
UC Berkeley
Berkeley, CA 94720-3140

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Ronald Tipper and Elizabeth Turner, Code 322BC
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13. ABSTRACT (Maximum 200 words)

We intend to answer whether marine animals can produce significant turbulent mixing. Two cruises were conducted in Norwegian fjords in winter, 1995 and spring, 1996. We used a microstructure CTD to measure the turbulent dissipation rate ε in euphausiid swarms directly. We also used ADCP spectral broadening measurements to estimate kinetic energy produced by euphausiid swimming. We revealed that euphausiid swarms have horizontal scales of 10^{-1}-10^{1}km and vertical scales of 10^{1}-10^{2}m. The abundance can reach to 10^{2}-10^{3} individuals m^{-3}. Within a swarm, the turbulence mixing can be significantly increased by their swimming up to the same order as wind induced mixing. This mixing produced by animal aggregations is very important to the local turbulence, acoustic, and optical fields, especially in coastal regions where zooplankton swarms are often found. We learnt that euphausiids may therefore be acting as "farmers in the sea." They can create enough turbulent mixing to bring continuous supply of nutrients from deep water into surface water for phytoplankton growth.

We also demonstrated that the spectral broadening measurements of an ADCP can be used to estimate the swimming velocities of marine macro-zooplankton. This new technology has opened a door to study *in situ* swimming behaviors of zooplankton.

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MEASURING THE INFLUENCE OF ANIMALS ON TURBULENCE IN THE SEA

Dr. Meng Zhou
Scripps Institution of Oceanography, UC San Diego, La Jolla, CA 92093-0202
(619)822-0046, mzhou@sjpoole.ucsd.edu

Dr. Mark E. Huntley
Scripps Institution of Oceanography, UC San Diego, La Jolla, CA 92093-0202
(619)534-3417, mhuntley@soest.hawaii.edu

Dr. Thomas M. Powell
UC Berkeley, Berkeley, CA 94720-3140
(510)642-7455, zackp@violet.berkeley.edu

Award number: N00014-96-1-0010

LONG TERM GOALS

Our aim is better understand the relation between biological and physical forces in the ocean. Our method of doing so is to use new technology to examine new concepts. Our interest is to understand how ocean physics influence marine organisms on scales ranging from the individual to the population, and also to explore the ways in which biological phenomena influence the physical environment.

OBJECTIVES

We proposed to measure animal-induced turbulence by two different methods. The first relies on an estimate of total kinetic energy dissipation rate, ε, based on ADCP-estimate kinetic energy produced by animal aggregations. The second relies on direct measurements of ε using a microstructure CTD. The principal goals are: (1) to compare direct and indirect measurements of turbulence generated by aggregations of marine euphausiids *in situ*; (2) to verify that such turbulence is animal-generated by measuring the production scales of turbulence; (3) to measure the turbulence produced by animals of different mass with different aggregation behavior.

APPROACH

Field measurements of ε have been integrated into an ongoing research program supported by the National Science Foundation. Field studies were carried out in fall (Oct-Nov, 1995) and spring (Apr, 1996) in Sørfjord and Ullsfjord, northern Norway, on three species of euphausiids.

WORK COMPLETED

Our field experiments were conducted from early October through early December 1995 and again in April 1996 in Sørfjord and Ullsfjord near Tromsø, Norway. Each survey started with a transect to acoustically map the zooplankton distribution, and then followed by a transect of MOCNESS tows. The ADCP echo intensity measurements were processed at real time, which allowed us to identify and to locate euphausiid swarms immediately after the ADCP and MOCNESS transects. Within a selected euphausiid swarm, MOCNESS tows were conducted to verify zooplankton species. In next 24 hours, the swarm was monitored by a series of ADCP transects to measure the spatiotemporal distribution of the euphausiids. The measurements of

spectral broadening and echo intensity were made together with a series of net tows and microstructure CTD casts at a time series station during this 24 h period.

In FY97, our efforts were made to process ADCP velocity data, to sort MOCNESS zooplankton samples, to calibrate ADCP echo intensity measurements with abundance and biomass estimates of euphausiids from MOCNESS catches, to develop mathematical algorithms to extract euphausiid swimming information from ADCP spectral broadening data, and to calculate the turbulence dissipation rates from microstructure CTD measurements.

RESULTS

1. Swarming and migration behaviors of euphausiids. ADCP echo intensity measurements can be used to estimate the abundance and biomass of zooplankton in the water column (Zhou et al.

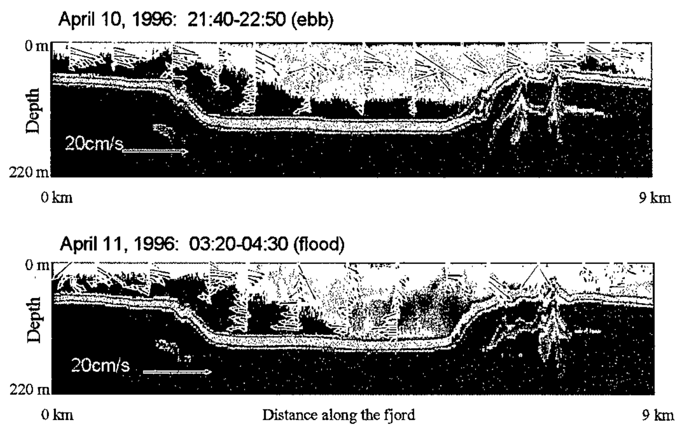

Figure 1. ADCP velocity and echo intensity measurements in Sørfjord. The vectors are along fjord and vertical components of velocities, and the color maps are the estimates of euphausiid abundance varying from 0 (blue)-300 individuals m^{-3} (red).

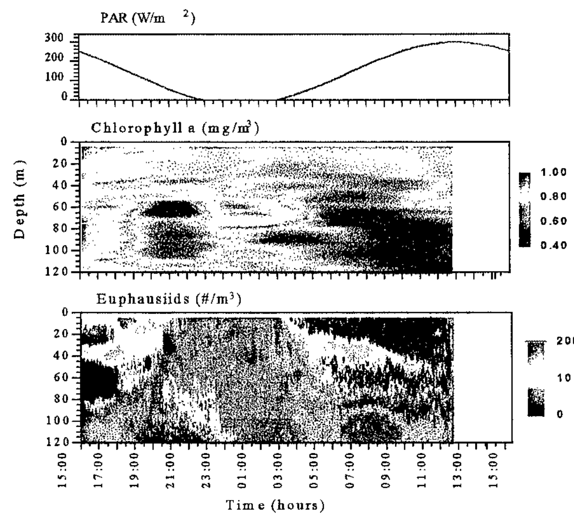

Figure 2. Time series measurements of PAR, Chlorophyll a and euphausiid abundance at a station in Sørfjord.

1994). Our MOCNESS catches and ADCP echo intensity measurements revealed strong swarming and migration behaviors of euphausiids (Figure 1). Zooplankton biomass in Norwegian fjords was dominated by two euphausiid and one copepod species. Both euphausiid species (*Thysanoessa rashii* and *T. inermis*) form dense aggregations. Each swarm consisted almost only of one species. The spatial scale of an euphausiid swarm varies from 10^{-1} to 10^{1} km, and its abundance varies from 10^{0} to 10^{3} individuals m^{-3}. The migration of euphausiids responded to the change of light (Figure 2). They stayed at the bottom during the day to avoid predators. The maximum abundance could reach to 10^{3} individuals m^{-3} due to their resting. They moved to the upper water column to feed phytoplankton at night. Due to grazing by high abundant euphausiids, the phytoplankton accumulated from day time photosynthesis were cleaned. Euphausiids moved down to the bottom at dawn.

2. Spectral Broadening. The spectral width of ADCP velocity measurements is proportional to the swimming velocities of targets (Zhou and Huntley 1996). Figure 3 shows 24 hour time series of vertical profiles of echo intensity and spectral broadening at a station located in the mid of the ADCP transect in Figure 1. Spectral broadening measurements revealed a 6 cm/s increase in spectral width due to the presence of a krill swarm near the surface. These results verify the

utility of ADCPs as a remote method for measuring zooplankton swimming velocities. The rate of energy production by a single euphausiid is approximately equal to 5.1×10^{-9} watts (Huntley and Zhou 1997). Thus, the turbulence dissipation rate produced by this euphausiid aggregation was approximately up to 1.5×10^{-2} cm^2 s^{-3} when the abundance reaches to 300 individuals m^{-3}.

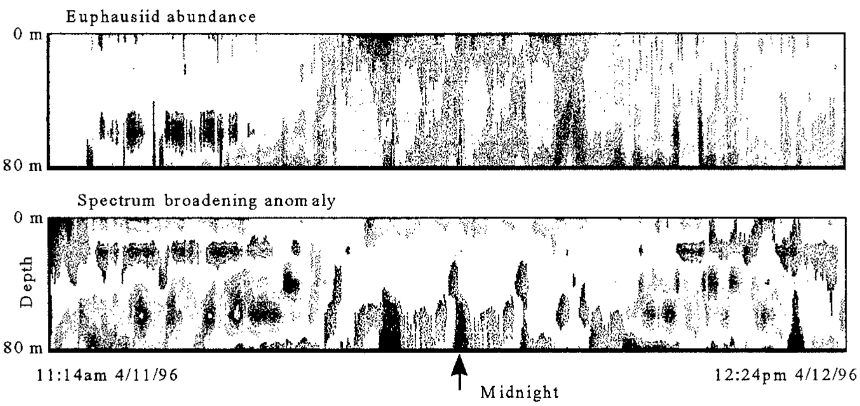

Figure 3. Time series of vertical profiles of echo intensity and spectral broadening at Station 7 in the Sørfjord. The upper panel is the abundance of euphausiids estimated from echo intensity measurements, which varies from 0 (blue) to 300 individuals m^{-3} (red). The lower panel is the anomaly of spectral broadening, which varies from 0 (blue) to 6 cm/s (red).

3. Direct turbulence dissipation rate measurements. We estimated the turbulence dissipation rate from the microstructure CTD data based on the theory developed by Ozmidov (1965), Thorpe (1977) and Dillon (1982). The results indicated that the turbulence dissipation rate varies from 10^{-4} to 10^{-2} cm^2 s^{-3} (Figure 4), which is in the same order as the dissipation rate estimated from ADCP spectral broadening measurements. We believed that this mixing was not produced by wind because the mixing was not surface intensified, which is usually the case due to strong velocity shear produced by wind stress near the surface.

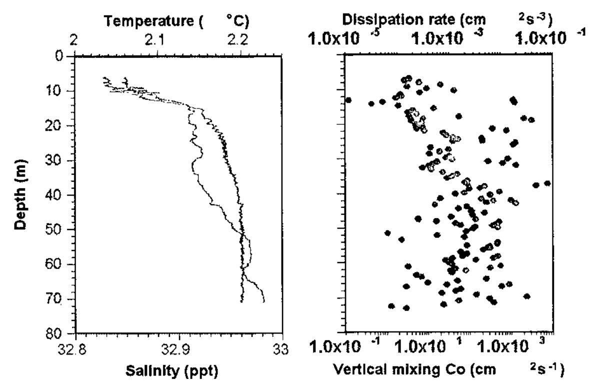

Figure 4. Vertical temperature and salinity profiles measured by a microstructure CTD, and the estimates of dissipation rates and vertical mixing coefficient in Sørfjord.

IMPACT

We have learnt that euphausiid swarms have horizontal and vertical scales of 10^{-1}-10^{1} km and 10^{1}-10^{2} m, respectively. The abundance can reach to 10^{2}-10^{3} individuals m^{-3}. Within a swarm, the turbulence mixing can be significantly increased due to their swimming up to the same order as wind induced mixing. This animal induced mixing may not be important to the global ocean due to limited zooplankton swarms, but it is very important to the local turbulence, acoustic, and optical fields, especially in coastal regions where zooplankton swarms are often found. We learnt that euphausiids may therefore be acting as "farmers in the sea." They can create enough turbulent mixing to bring continuous supply of nutrients from deep water into surface water for phytoplankton growth.

We also demonstrated that the spectral broadening measurements of an ADCP can be used to estimate the swimming velocities of marine macro-zooplankton. This new technology has opened a door to study the *in situ* swimming behaviors of zooplankton. Torres and Childress (1983) indicated that there is a linear relation between the swimming velocity and metabolic rates of

marine animals. Thus, the remote measurements of swimming velocities can be used directly to estimate *in situ* metabolic rates of zooplankton.

RELATED PROJECTS

Zooplankton distributions in the ocean are determined by advection, behaviors, and population dynamics. Zooplankton not only play the tropic link between phytoplankton and fish, but also influence the acoustic and optical fields. Our recent efforts have been made to understand these processes and further to predict the spatiotemporal distributions of zooplankton in the ocean (Zhou et al. 1994; Huntley et al. 1995; Huntley and Zhou 1996; Huntley et al. 1996; Zhou and Huntley 1996; Zhou and Huntley 1997a; Zhou and Huntley 1997b). Drs. M. Zhou and M.E. Huntley currently have 4 projects: 1) Aggregation and metabolism in northern boreal euphausiids (NSF), 2) U.S. GLOBEC: Aggregation dynamics of Antarctic krill, *Euphausia superba Dana* (NSF), 3) U.S. JGOFS's Southern Ocean process study: Zooplankton processes (NSF), 4) U.S. GLOBEC: A zooplankton population dynamics model in the California Current region (NSF). The results from this project provide us the basic understanding of aggregation and swimming behaviors of zooplankton and their contribution to the turbulent mixing in the ocean, which will further to improve our zooplankton models.

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<pi> Mark E. Huntley
<pi_address> Scripps Institution of Oceanography, UC San Diego,La Jolla, CA 92093
<pi_email> mhuntley@soest.hawaii.edu
<pi_phone1> (619)534-3417
<pi_phone2> (808)923-4627
<pi_fax1> (619)534-7442
<pi_fax2> (808)923-4719

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